UPPER-AIR CURRENTS AT HONOLULU, T. H.

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A large amount of data regarding upper-air currents has been obtained at Honolulu, Territory of Hawaii, from the pilot-balloon observations taken for aviation purposes in its environs at the naval station, Pearl Harbor. Before January, 1924, few balloon flights were followed above 6 kilometers, so that studies of these data made by Blair (1) and Beal (2) were limited to winds of moderate altitude. It is the purpose of this article to discuss upper winds over Pearl Harbor (lat. 21° 22′ N., long. 157° 57′ W.), based on an analysis of 159 flights made between July, 1924, and July, 1927, all of which were followed above 5 kilometers and in one instance to 30 kilometers. These were evenly distributed over the three years and provide good material for the study of trade winds, although a larger number of flights was desired. I am indebted to J. F. Voorhees, meteorologist, United States Weather Bureau, Honolulu, for having placed them at my disposal. Although situated upon an island within the Tropics, Honolulu has both a very small annual rainfall (25.41 inches) and a large percentage of days with cloudless sky, which combine to make it an excellent location for aerological investigation.

Honolulu is situated southwest of the permanent high-pressure center of the eastern Pacific in an area where the NE. trades are prevalent throughout the whole year. From June to August winds from east to northeast blow for over 93 per cent of the time, and even in the winter season, when most interrupted by winds set up by cyclonic depressions, trades persist for 66 per cent of the time.

The percentage frequency of winds blowing from 16 points of the compass for half-kilometer levels up to 11 kilometers is given in Table 1.

TABLE 1.—*Frequency of winds from various directions at different altitudes above Pearl Harbor, Honolulu, 1924–1927*

Altitude (kilometers)	Number of observations	N.	NNE.	NE.	ENE.	E.	ESE.	SE.	SSE.	S.	SSW.	SW.	WSW.	W.	WNW.	NW	NNW.
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Surface	141	15	5	18	35	11	1	3	1	...	1	2	1	...	...	1	6
0.25	154	3	1	23	44	13	3	2	1	...	2	1	2	3	2	...	1
.50	157	...	4	10	45	24	2	2	...	...	3	1	3	3	3	...	3
.75	155	1	1	6	44	26	4	3	1	...	1	2	3	2	3	1	1
1.0	159	3	1	8	30	26	10	3	1	...	2	1	3	3	4	1	3
1.5	157	4	6	7	16	27	10	4	4	1	2	2	3	3	4	4	4
2.0	154	2	6	11	17	17	12	8	5	1	3	4	3	4	2	3	2
2.5	156	3	5	11	14	17	15	4	5	1	4	6	3	3	2	3	4
3.0	153	7	5	12	11	10	14	9	5	1	2	5	5	5	3	2	4
3.5	155	6	7	13	12	8	12	6	3	1	3	6	8	3	3	8	6
4.0	158	8	4	8	11	10	4	7	4	3	4	4	10	6	6	7	5
4.5	158	2	8	6	8	8	5	8	6	2	6	6	10	6	6	4	8
5.0	154	5	4	7	10	6	6	4	5	1	6	10	9	6	5	9	7
5.5	151	4	7	5	9	5	7	3	2	3	8	10	7	8	9	5	8
6.0	131	5	4	8	8	5	5	2	5	2	8	5	5	15	9	7	8
6.5	90	9	4	7	10	1	...	...	2	1	7	6	9	12	10	9	13
7.0	74	12	7	7	11	1	...	3	1	...	4	6	12	7	12	10	8
7.5	68	7	7	6	12	2	2	...	3	2	2	4	16	3	12	16	7
8.0	63	6	5	6	13	...	...	3	2	3	...	5	13	11	14	11	8
8.5	53	6	4	11	4	4	2	4	2	...	2	6	6	15	17	17	2
9.0	41	5	2	7	5	5	2	2	5	...	...	7	2	20	10	17	10
9.5	35	3	3	9	9	...	6	3	3	...	3	3	11	17	9	14	9
10.0	27	4	7	7	11	4	4	4	...	7	...	4	15	7	11	11	4
10.5	27	11	...	15	11	...	4	4	...	...	4	4	7	11	11	11	7
11.0	24	8	4	17	4	8	...	...	4	...	...	...	8	13	8	13	13

The NE. winds at the surface veer with increasing altitude through E. and SE. to SW. and NW. until at 12 kilometers the winds have completed the circuit through 360°, and are blowing again from the NE. Only 9 balloons were followed above 12 kilometers and these would indicate northerly and easterly winds to 20 kilometers. In Figure 1 are given the directions of all flights above 11 kilometers which, although subject to considerable individual error through leaks in balloon fabric and vertical currents, give evidence of the existence of the upper NE. trade winds.

While the wind veers round as viewed from outside the earth in a clockwise direction it does not do so at a regular rate; there are two main currents continuing throughout the year, with intervening bands of winds with direction varying with the season. The two predominating wind currents are the NE. trades up to 2 kilometers and the NW. antitrades from 7 to 12 kilometers. Between these two main currents are southerly winds with direction depending upon the season. Above the NW. antitrade is the thin upper trade wind reaching to the tropopause. In the tropopause as Dobson has found in England the winds are subject to wide vagaries, both in direction and velocity. Above the trades, the great current of air is the NW. antitrade which, it is interesting to note, Ficker (3) has found playing an equally important rôle at Teneriffe in approximately the same latitude in the Atlantic Ocean.

In order to investigate the variation in the heights of winds with season, the observed wind velocity at each half kilometer was resolved into north-south and east-west components, the components being grouped in periods of two months. Although the results obtained at Honolulu by this method are believed to represent the state of affairs normally existent in nature, there are conditions not strikingly dissimilar when the method would lead to fallacious conclusions. Thus a belt of very strong winds blowing for nine-tenths of the time may sweep the balloons so far from the observer that they are lost in distance. The balloons released when light or contrary ground winds occur will continue to be observed through the belt of strong winds usually present into levels which are probably calmer than their normal state. There is a small selective effect in the 159 flights here discussed each of which is followed to at least 5 kilometers; the wind velocities up to 4 kilometers altitude are about 15 per cent less for each level than those given by Beals for 1,265 flights taken daily. The velocity components up to 10 kilometers are given in Tables 2 and 3.

TABLE 2.—*North-south wind components at Honolulu*

[The plus sign (+) indicates north component]

Altitude (kilometers)	Jan.-Feb., m. p. s.	Mar.-Apr., m. p. s.	May-June, m. p. s.	July-Aug., m. p. s.	Sept.-Oct., m. p. s.	Nov.-Dec., m. p. s.
0.25	+0.62	+1.18	+1.21	+2.25	+2.12	+1.17
0.50	0.00	+1.14	+1.00	+2.33	+2.04	+0.23
0.75	0.00	+0.74	+0.75	+1.78	+1.92	+0.09
1.0	−0.59	+0.69	+0.75	+1.80	+1.79	−0.41
1.5	−1.19	−0.09	+0.29	+0.75	+1.37	+0.20
2.0	−2.39	−0.66	−0.57	+0.64	+1.07	−0.29
2.5	−2.30	+0.31	−0.89	+1.06	+1.06	−1.46
3.0	−1.87	+0.19	−1.43	+1.05	+1.81	−0.22
3.5	−2.47	+1.05	−1.32	+0.66	+2.53	−0.18
4.0	−2.17	+1.69	−1.57	−0.20	+2.44	−0.73
4.5	−1.46	+1.73	−1.28	−0.64	+2.47	−0.27
5.0	−1.35	+1.22	−1.03	−0.87	+2.34	−0.21
5.5	−0.21	+1.45	−1.86	−1.59	+2.64	+0.39
6.0	−0.08	+3.28	−1.74	−1.25	+3.94	+0.39
6.5	+1.61	+2.21	−1.07	−2.28	+4.89	+1.68
7.0	+2.53	+2.30	−1.00	−3.08	+4.02	+2.16
7.5	+4.56	+4.88	−1.24	−4.18	+4.54	+2.58
8.0	+8.37	+2.92	−0.73	−3.59	+4.83	+1.93
8.5	+7.77	+3.18	+0.08	−2.27	+5.33	+1.98
9.0	+9.97	+7.62	−0.95	−6.07	+3.99	+4.30
9.5	+8.00	+5.13	−4.63	−5.95	+4.99	+6.21
10.0	+3.50	+4.33	+0.20	−5.47	+5.46	+4.68

TABLE 3.—*East-west wind components of velocity at Honolulu*

[The plus sign (+) indicates west wind]

Altitude (kilometers)	Jan.-Feb., m. p. s.	Mar.-Apr., m. p. s.	May-June, m. p. s.	July-Aug., m. p. s.	Sept.-Oct., m. p. s.	Nov.-Dec., m. p. s.
0.25	−2.56	−2.02	−2.08	−5.32	−3.41	−2.43
0.50	−3.87	−2.45	−2.60	−5.79	−4.05	−2.73
0.75	−4.17	−2.53	−2.37	−6.28	−4.84	−2.53
1.0	−3.76	−1.61	−2.15	−6.66	−4.67	−2.01
1.5	−2.60	−1.86	−1.87	−5.03	−3.01	−1.51
2.0	−2.50	−1.56	−2.15	−3.89	−2.36	−1.38
2.5	−2.65	−1.03	−1.93	−2.96	−2.30	−2.64
3.0	−1.46	+0.09	−1.18	−2.33	−2.12	−2.67
3.5	−0.61	+1.06	−1.23	−1.89	−1.68	−1.74
4.0	−0.10	+2.44	−1.00	−0.81	−0.55	−1.56
4.5	+0.27	+2.64	−1.04	−0.99	−0.16	0.00
5.0	+1.80	+3.99	−1.77	−0.26	+0.74	−0.02
5.5	+3.58	+5.29	−1.05	+0.62	+1.44	+1.30
6.0	+2.04	+5.68	−0.33	+2.75	+2.44	+0.75
6.5	+3.07	+7.95	+0.49	+3.98	+2.42	+1.03
7.0	+4.82	+5.36	+0.50	+3.32	+2.49	+0.77
7.5	+5.48	+4.20	−0.40	+5.50	+2.28	+2.08
8.0	+6.38	+8.78	−2.94	+5.84	+1.20	+4.11
8.5	+13.0	+9.88	−4.70	+7.14	+2.54	+3.51
9.0	+12.9	+10.22	−5.22	+6.57	+7.48	+2.20
9.5	+10.94	+5.73	−8.79	+8.63	+7.27	+2.84
10.0	+10.15	+6.33	+8.70	+8.25	+3.23	+1.96

Although the north-south components at the surface are strongest during May to September, it is to be noted that above 1 kilometer the absolute velocities are greater during January to April. The steeper temperature gradients set up during the winter months between the temperate zone and the equator produce a more vigorous circulation at the higher levels. The variation of the heights at which winds blow is most clearly seen from Figures 2 and 3, derived from the above tables.

(1) The NE. trade winds are shallowest from November to February when they have a depth of 1 kilometer and deepest from July to October when they are 4 kilometers thick. The upper NW. wind is weakest and thinnest during the northern summer from May to August. SE. winds would appear to interrupt the NW. current during May and June but there are few observations available to establish this result. There is a much greater development of winds from the south during summer which may be due to increased convection or to the dumping of air into the Northern Hemisphere by the SE. trades which are much stronger during these months. The United States Pilot Charts give their usual northern limit as 5° N. during June to August and 5° S. during December to February. Neither of these forces acts directly. The overflow from the south would have been deflected by the earth's rotation from this direction long before it reached Honolulu unless guided by other forces. The effect of the increased vertical currents in setting up stronger trades when the sun is overhead in June does not have its counterpart in the southern Pacific, where the trade winds are weakest during December and January, the months in which the sun's altitude is greatest.

From the velocity components the relative displacement of air east or west, and towards the Equator or the Pole was obtained for each kilometer stratum by multi-

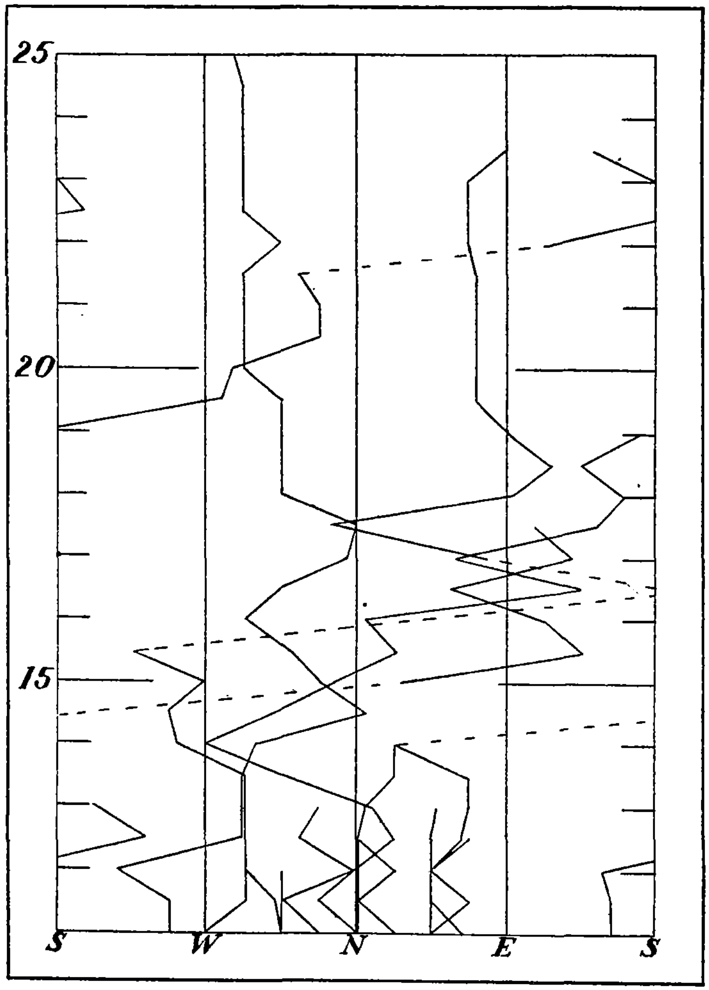

FIGURE 1.—Direction of pilot balloons above 11 kilometers at Pearl Harbor, Honolulu. Although showing wide variations there is evidence of northerly winds up to 20 kilometers

plying the velocity of each stratum by its density. The adopted mean velocity for layers up to 9 kilometers was obtained by taking the mean of the two monthly velocities, above 9 kilometers, owing to the uneven distribution of data the mean of all flights was used. Lacking density data based on observations at Honolulu, an air density midway between that found for Equator and for Canada was used. Since the air has the same density at these places at an altitude of 11 kilometers and has a maximum difference at 1 kilometer of only 5 per cent the error introduced by assuming a density midway between them must be slight. The relative displacement of air is given in Table 4.

TABLE 4.—*Relative displacement of air in layers 1 kilometer thick to an altitude of 14 kilometers*

[Air displacement =10×wind velocity in m/s×density of the air. Plus sign indicates north or east wind]

Height, kilometers	Density, g/m	North velocity component, m. p. s.	North displacement	West velocity component, m. p. s.	West displacement
0.5	3.32	+1.12	+3.98	−3.58	−11.88
1.5	3.00	+0.22	+0.66	−2.65	−7.95
2.5	2.70	−0.37	−1.00	−2.25	−6.08
3.5	2.42	+0.04	+0.10	−1.02	−2.47
4.5	2.19	−0.09	−0.20	+0.12	+0.26
5.5	1.98	+0.14	+0.28	+1.86	+3.68
6.5	1.78	+1.17	+2.08	+3.16	+5.62
7.5	1.60	+1.86	+2.98	+3.19	+5.10
8.5	1.36	+2.68	+3.64	+3.28	+4.46
9.5	1.13	+2.29	+2.59	+4.44	+5.02
10.5	0.98	+2.71	+2.66	+3.91	+3.83
11.5	0.86	+6.84	+5.88	+1.67	+1.44
12.5	0.76	+5.93	+4.51	−0.35	−0.27
13.5	0.66	+4.28	+2.82	+3.06	+2.01

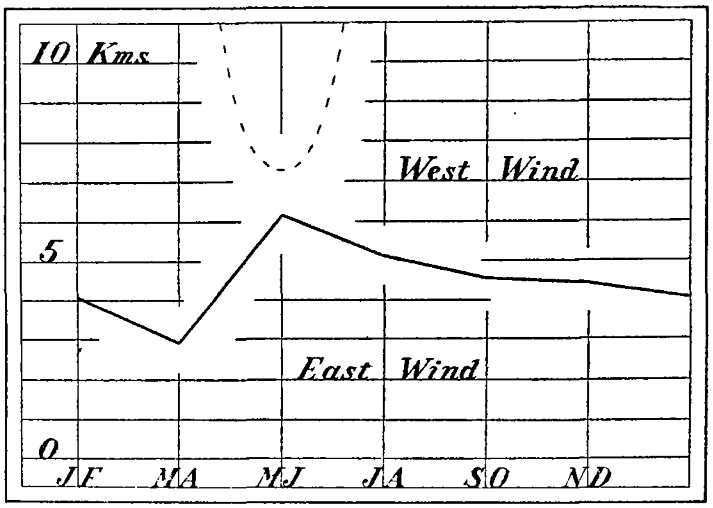

FIGURE 2.—Variation of height of east-west wind components during year. During May–June easterly winds prevailed above 6 kilometers

Up to 13.5 kilometers the air mass moved toward the east is 1.1 times as much as the air moved toward the west; making use of the velocities determined from the few flights available up to 25 kilometers altitude, it is found that there is the same amount of air transported toward the east as toward the west. There is a great preponderance of air movement toward the Equator; up to 13.5 kilometers the polar inflow to the Equator is twenty-seven times the outflow. Owing to the frequency and strength of southerly winds about the 20-kilometer level the excess of polar inflow computed from all flights up to 25 kilometers is reduced to 9.5 times the outflow from the Equator. Above the 25-kilometer level the density becomes so small that, even should southerly winds with exteremely high velocities occur at these heights, the total air mass moved toward the Equator would remain much greater than that moved poleward.

The trade winds have, until recently, been explained as the return flow at surface levels of the warm air which, having risen at the Equator to great altitudes, flows off toward the Pole; the rotation of earth deflecting the returning winds so that their approach to the Equator has an angle of 45° therewith. This simple explanation has been attacked by modern meteorologists, notably Sir Napier Shaw. To the modern view the intertropical circulation may be considered as currents of air flowing in between centers of high pressure guided along their course toward the Equator by pressure distribution and then after joining the equatorial current finding their way to high latitudes either at great altitudes or on the appropriate side of high-pressure centers. The old view would require above every point in the intertropical area an equivalence of air moving north and south. The Honolulu data show clearly that there is at that point not an equal north and south flow but a great mass of air being carried in toward the Equator. Above the Hawaiian Islands there is a continuous equatorward current of polar air; where this current works back to high latitudes is not clear.

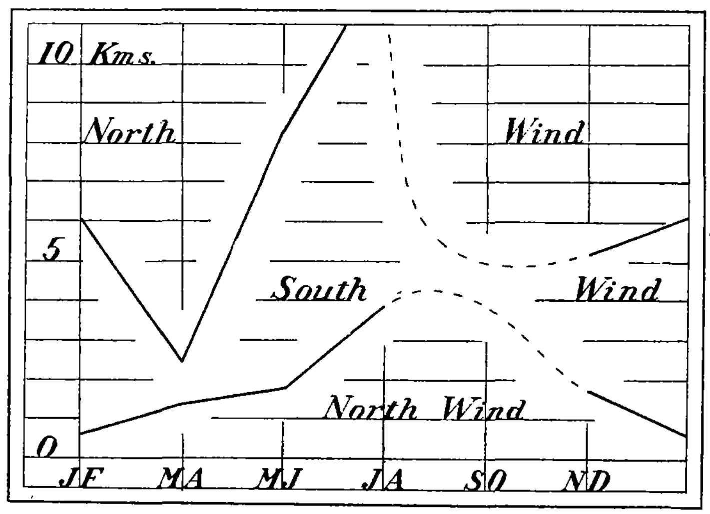

FIGURE 3.—Variation in height of north-south wind components during year. In September–October northerly winds occurred at all heights up to 11 kilometers

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